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COMPLEX FOR PRODUCTION OF SILICATE MELT FROM ASH WASTES

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A new complex is proposed for obtaining silicate melt from ash wastes. A mathematical model that describes melting of the batch in a furnace using combined sources of thermal energy — electric and gas — is formulated.

The important amount of ash and slag wastes that accumulate in the dumps at power plants worsens the environment in the regions where they are located. They harm all living things, reduce soil fertility, and increase the radiation pollution and dustiness of the regions. The basic content of these wastes is incombustible mineral residue, which is good glass-forming feedstock. However, the treatment temperature (primarily melting) of this technogenic material is much higher than the melting point of natural feedstock. Increasing the manufacturing process temperature in traditional melting units involves a nonproportional increase in power consumption. The existing melting methods [1, 2] do not allow obtaining a melt from ash due to the low temperatures inside the furnace.

We analyzed an important new complex based on use of a combined source of thermal energy for production of a silicate melt from ash wastes.

Experimental setup. The thermal conditions for obtaining the required viscosity of the ash melt can be created by converting electrical energy into thermal energy (electric furnaces) or simultaneously by burning fuel and converting electrical energy into thermal energy (gas-electric furnaces). Two types of convective flows caused by burning gaseous fuel and additional electric heating are a special feature of gas-electric furnaces. In these furnaces, the molten mass of bulk material is used as resistance. Additional electric heating increases the output and efficiency, and usually significantly improves the quality of the melt.

The job of the additional electric heating is to release the required amount of heat into the melting tank. Additional heat is consumed for heating the entire melt in the melting tank by heat exchange and partially to compensate for heat losses through the walls of the furnace.

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The experimental setup whose diagram is shown in Fig. 1 was developed to study obtaining a melt from thermal electric generating station ash by combined heating of the ash (gas and electric arc) and practically test the working capacity of the equipment.

Direct current power source *3* with gradual current regulation is used for powering electrodes *1*, *2*. The arbitrary working voltage of the power source is 250 V. The required power at the nominal current (400 A) is a maximum of

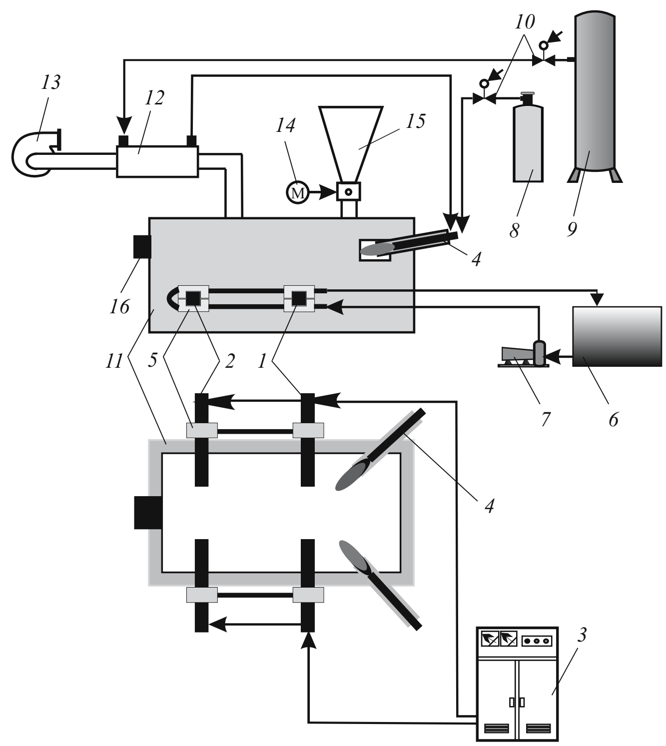

Fig. 1. Diagram of the experimental setup.

128 kW. The energy capacity of the efficiency is a minimum of 84%.

Graphite or molybdenum pencil electrodes are used in gas-electric furnaces. Their position in the melting space is a function of the size and design of the melting tank and the thermal conditions of operation of the furnace.

The furnace melting tank is divided into two parts.

Gas burners *4* and the first pair of electrodes *1* are located in the first part of the furnace. This part is designed for heating and subsequent melting of the bulk material with two mutually complementary heat flows: from the gas space at the top and from the additional electric power at the bottom. The values of the temperatures and heat flows at bottom and top are determined by consumption of the fuel burned and electric power consumption.

An additional pair of graphite electrodes *2* is located in the second part of the furnace and it serves to maintain the high melt temperature at the outlet from the melting tank.

Cooling jackets *5* installed from outside the furnace are made for cooling the current supplies of electrodes *1* and *2*. The cooling system is a circulating stream of a liquid (water) in a closed system: tank with water *6* → centrifugal pump *7* → cooling jacket *5* → tank *6*.

The gas-supply system consists of propane tank *8*, receiver *9*, control valves *10*, and two burners *4*. The receiver is primarily intended for evening out pressure fluctuations caused by pulsing feed and continuous flow. The air in the receiver is delivered by a compressor. Rotameters are installed in the system to regulate gas and air flow. The burners are located in the upper rear part of furnace *11* so that their nozzles are directed on the material — ash, which is in the region of the ends of the first pair of electrodes. To increase the jet temperature, the air fed to the burner passes through heat exchanger *12*, installed in the stack gas discharge pipe. The stack gases are sucked out of the internal space of furnace *11* by fan *13*.

A batcher is installed on the top of furnace *11* for feeding the material. Batching of the material is regulated by changing the rotation rate of direct current motor armature *14*.

The material is poured into furnace *11* to the level of the electrodes and is uniformly distributed over the entire space of the first part of the furnace. A gas mixture (propane + air) is fed to the gas burners and is ignited with an oscillator. The necessary ratio of the propane and air flows is established by the rotameters to attain a rational jet temperature.

In the first stage of startup, the internal space of the furnace and material is heated to the melting point. After reaching the melting point, a conductive ash melt is formed, creating intensive convective currents between electrodes *1*, i.e., combined (gas and electric arc) heating of the material is conducted. When convective flows form, the following characteristics are observed in the electrodes: $I = 320$ A, $U = 120$ V (time of startup). The temperature of the melted material is changed by varying the power fed to the electrodes, where the current is gradually regulated. In subsequent operation, these characteristics are within the ranges of $I = 250 - 320$ A and $U = 100 - 200$ V.

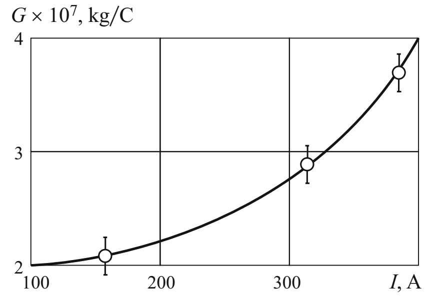

Fig. 2. Dependence of specific erosion of the graphite electrode G on current I passing between electrodes in the melt.

During operation of the furnace, the ash is fed into the melting basin by batcher *15*. The melt formed is moved to notch *16* and reaching the ends of the first pair of electrodes, current is passed through the melt and the convective flow correspondingly passes into the second part of the furnace. The second pair of electrodes is designed to keep the melt temperature constant in coming out of the furnace. The melt spontaneously leaves the furnace when the notch is reached.

Due to unavoidable erosion of the electrodes inside the furnace, it becomes necessary to automate the feed during operation of the heating unit to maintain the assigned parameters of the current passing between the electrodes. As a result of the studies conducted, the dependence of the specific erosion of the graphite electrodes on the current passing between them was obtained (Fig. 2). The dependence found can be used to obtain the data necessary for selecting an asynchronous electric motor and a motor control system to automatically adjust the electrodes when they are eroded. In addition, use of a modern electric drive ensures partial automation of the manufacturing process for keeping the melt temperature constant.

Mathematical model. The boundary-value problem of nonstationary turbulent conjugate convective-conductive heat transfer in the closed volume of a furnace is examined (Pos. *11* in Fig. 1).

In performing the analysis, it is assumed that the gas flow regime in the furnace cavity is turbulent. The gas is considered a viscous, heat-conducting, incompressible, Newtonian fluid. The hydrodynamic and thermophysical characteristics of the gas are assumed to be constant, except for the thermal conductivity. Movement of the gas phase and heat transfer in the inner volume is considered three-dimensional. Heat exchange by radiation based on the Rosseland approximation (or the approximation of an optically thick layer) is also taken into consideration in the gas cavity [3, 4]. It is hypothesized that high-temperature gas enters the furnace cavity from the burners and heats the inside of the furnace.

In this setup, heat transfer in the examined area is described by a system of nonstationary, Reynolds-averaged, Navier – Stokes equations for the gas phase [5] and a thermal

conductivity equation for the solid phase [6]. The standard $k-\varepsilon$ model is used as the closed model of turbulence [7]. For simplicity, it is useful to represent the system of mathematical physics equations in tensor form:

for the gas phase:

$$\frac{\partial U_i}{\partial x_i}=0;$$

$$\rho_g \frac{\partial U_i}{\partial t}+\rho_g U_j \frac{\partial U_i}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\mu_g \frac{\partial^2 U_i}{\partial x_j\,\partial x_j}+$$
$$\frac{\partial}{\partial x_j}\left(\rho_g c_\mu \frac{k^2}{\varepsilon}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)-\frac{2}{3}\rho_g k\delta_{ij}\right);$$

$$\rho_g C_{pg}\left(\frac{\partial T_g}{\partial t}+U_j \frac{\partial T_g}{\partial x_j}\right)=$$
$$\frac{\partial}{\partial x_j}\left(\kappa_g \frac{\partial T_g}{\partial x_j}+C_{pg}\rho_g \frac{c_\mu k^2}{\Pr_t\,\varepsilon}\frac{\partial T_g}{\partial x_i}+\int_0^\infty \frac{3}{3\chi_\lambda}\frac{\partial e_{b\lambda}}{\partial x_j}\,d\lambda\right);$$

$$\frac{\partial k}{\partial t}+U_j \frac{\partial k}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\nu_g+\frac{c_\mu k^2}{\sigma_k \varepsilon}\right)\frac{\partial k}{\partial x_j}\right]+$$
$$c_\mu \frac{k^2}{\varepsilon}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}-\varepsilon;$$

$$\frac{\partial \varepsilon}{\partial t}+U_j \frac{\partial \varepsilon}{\partial x_j}=\frac{\partial}{\partial x_j}\left[\left(\nu_g+\frac{c_\mu k^2}{\sigma_\varepsilon \varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+$$
$$\left(c_{1\varepsilon}c_\mu \frac{k^2}{\varepsilon}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}-c_{2\varepsilon}\varepsilon\right)\frac{\varepsilon}{k};$$

for the solid phase:

$$\rho_i C_{pi}\frac{\partial T_i}{\partial t}=\frac{\partial}{\partial x_j}\left(\kappa_i \frac{\partial T_i}{\partial x_j}\right),$$

where U_i are the projections of the velocity vector on the axis of a Cartesian system of coordinates; x_i are the coordinates of the Cartesian system of coordinates (x, y, z); t is the time; ρ_g is the density of the gas; p is the pressure; μ_g is the heat capacity of the gas at constant pressure; C_{pg} is the heat capacity of the gas at constant pressure; T_g is the temperature of the gas; κ_g is the thermal conductivity of the gas; λ is the radiation wavelength; $e_{b\lambda}$ is the spectral emissivity (radiation beam density) of an absolutely black body; χ_λ is the absorption coefficient of the medium; ρ_i is the density of the ith element of the solid material; C_{pi} is the heat capacity of the ith element of the solid material at constant pressure; T_i and κ_i are the temperature and thermal conductivity of the ith element of the solid material; k is the kinetic energy of turbulence; $\delta_{ij}=\begin{cases}1, & i=j\\ 0, & i\neq j\end{cases}$ is the Kronecker symbol; ν_g is the molecular kinetic viscosity coefficient of the gas; ε is the rate of dissipation of the kinetic energy of turbulence; c_μ, $\Pr_t$, σ_k, σ_ε, $c_{1\varepsilon}$, $c_{2\varepsilon}$ are the empirical constants of the $k-\varepsilon$ model of turbulence.

The bulk material and air, characterized by the ambient temperature, are initially present in the furnace. A gas mixture (propane + air) is fed to the gas burners ignited with an oscillator. After this, the high-temperature gas flow formed enters the furnace cavity, which intensifies heat transfer processes. Boundary conditions of the first kind that determine the constant value of the rate in the direction of the axis of the burner are set out for the velocities in the zone of feeding the gas flow into the furnace. In the zone where the gas flow goes out, boundary conditions of symmetry are established.

The internal furnace space and filling material are heated to the melting point in the first stage of startup.

Boundary conditions:

Boundary conditions that account for convective heat exchange are recorded on the outer boundaries of the containment structure of the furnace and the environment:

$$-\kappa_i \frac{\partial T_i}{\partial \vec{n}}=\alpha\,(T^e-T_i),$$

where i corresponds to the material of the containment structure; α is the heat-exchange coefficient; $\vec{n}$ is the unit vector of the outer normal to the boundary; T^e is the ambient temperature.

In all sections of the region, the solution (except for the phase boundary) where conjugation of materials with different thermophysical parameters takes place, conditions of the fourth kind were satisfied

$$\begin{cases} T_i=T_j; \\ \kappa_i \dfrac{\partial T_i}{\partial \vec{n}}=\kappa_j \dfrac{\partial T_j}{\partial \vec{n}}, \end{cases}\Big|\, i\neq j$$

on the phase transition boundary S:

$$\begin{cases} T_m\big|_S=T_g\big|_S=T^*; \\ \kappa_m \dfrac{\partial T_m}{\partial \vec{n}}\Big|_S-\kappa_g \dfrac{\partial T_g}{\partial \vec{n}}\Big|_S=L\rho_m \dfrac{\partial S}{\partial t}, \end{cases}$$

where T_m is the temperature of the melt; T^* is the melting point of the batch; κ_m and ρ_m are the thermal conductivity and density of the melt, respectively; L is the specific heat of the phase transition; $\dfrac{\partial S}{\partial t}$ is the rate of movement of the free boundary; on hard walls, conditions of “sticking” are set for the rate.

After reaching the melting point, a conductive ash melt is formed, creating intensive convective flows between the

electrodes, i.e., combined (gas and electric-arc) heating of the material takes place. At this time, boundary conditions of the second kind on the electrodes — constant heat flow — are added.

It is necessary to consider that the melt begins to move when the melting point is reached, i.e., melt movement is formed.

Stokes equations describing the slow flow of the melt itself are thus added in the second stage of the mathematical description of formation of a melt.

The boundary-value problem formulated with the corresponding initial and boundary conditions describes formation and movement of a melt in conditions of turbulent gas heating and conductive heat transfer in the elements of a containment structure.

A complex was thus developed for obtaining a melt from ash wastes using a combined source of thermal energy (electric and gas heating). A mathematical model describing the complete process of heating the furnace and melting the batch in it was formulated.

The studies conducted open up areas for using a silicate melt in technologies for production of mineral fibres, glass crystal articles, etc.

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